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Driving performance and workload assessment of drivers with tetraplegia: An adaptation evaluation framework

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Abstract—The purpose of this study was to establish a baseline for further research on adaptation evaluation for drivers with disabilities. Driving performance and workload for 26 drivers with spinal cord injuries (tetraplegia) was studied and compared to a matched group of able-bodied drivers in a driving simulator. Drivers with tetraplegia used two types of hand-operated controls for accelerating and braking. Able- bodied drivers drove with standard pedals. The drivers with tetraplegia performed the driving task equally as well as the control group but had a slightly longer reaction time (10%). Workload assessment revealed that drivers with tetraplegia experienced a significantly greater time pressure and spent more effort than did the able-bodied drivers. They were also more tired from braking and accelerating. The drivers with tetraplegia using separate levers had greater standard deviation in lateral lane position (7 cm), while those using a combined lever were more tired from braking and accelerating. Observed differences could be interpreted as indicators of insufficient adaptation.

Key words: *adaptation evaluation, assessment, driving performance, driving simulator, spinal cord injury.*

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INTRODUCTION

In the USA, the annual incidence rate for spinal cord injuries (SCI) is 30–40 cases per million inhabitants or 8,000–10,000 SCI patients annually according to the National Spinal Cord Injury Statistical Center (NSCISC) (1,2). This number is probably too low due to significant under-reporting, according to NSCISC. The corresponding incidence rate for Sweden is 13 cases per million people annually (3). Spinal cord injury is a typical young male diagnosis. Median age at injury is approximately 25 years, and over 80 percent of SCI patients are males. The current trend is that both average age at accident and female proportion are increasing.[1] Between 35–50 percent of the injuries are caused by traffic accidents, but also falls (20–30 percent) and sports accidents (10–20 percent) contribute significantly.

Approximately 50 percent of the SCI population consists of paraplegics, and the other 50 are tetraplegics (2). All tetraplegics and most paraplegics depend on mobility aids such as wheelchairs for short-range transportation. If the injury is located below the fourth

[1] Kreuter M. Spinal cord injuries—causes, gender, and age distribution. Spinal Unit at Sahlgrenska Hospital, Gothenburg, Sweden, personal communication, 1997.

cervical vertebra and if there are no additional complications, the prospects of becoming a licensed driver are good, as long as the right adaptation is provided (4). The opportunity to independently drive a car substantially contributes to increased quality of life and increased possibilities of participating in daily life activities (5,6). Public transportation cannot offer the same level of flexibility and independence.

Standard-production cars are not designed for drivers with disabilities and usually have to be adapted according to the individual driver's resources and limitations. Koppa (7) identified three different areas where physically disabled drivers require provision: *ingress/egress*, *primary and secondary controls*, and *occupant protection*. A driver with disabilities provided with an adequate adaptation is not a *handicapped driver* in the sense that he or she would be a poorer driver compared to an able-bodied driver. A handicap is caused by a mismatch between an impaired person's abilities and the environmental demand (8). The right adaptation should compensate for a driver's impairment and thus eliminate a potential handicap while the impairment still remains.

There are no common international regulations and requirements on how to adapt cars for drivers with disabilities (9). The national differences can be considerable and inconsistent. The national regulations are often incomplete and vague. However, a general rule that usually applies is that a disabled person can be allowed to drive if the disability can be fully compensated for by adapting the vehicle. There do exist some general guidelines for car adaptations for drivers with disabilities (10,11) but these are far from comprehensive. Occasionally, tests are carried out to ensure that disabled persons' available resources (e.g. strength, reaction time, and reach) are sufficient and to determine the adaptation needs (12,13). However, there are no standardized evaluation tests that can be used to verify that the right adaptations have been provided (9,14). Koppa (7) claimed that a driver with disabilities should be able to operate all vehicle controls at the same performance level as a non-disabled driver in a standard car. This implies that an adaptation evaluation should be based on a comparison with non-disabled drivers driving standard cars. An adaptation evaluation should, at least, consider aspects such as crashworthiness (passive safety), functionality (active safety), workload, and comfort/discomfort.

Driving a car is a complex and highly dynamic task, and thus it is important to determine which aspects of the driving tasks are critical for drivers with SCI (15). A widely-used driving task model distinguishes three levels: *control*, *maneuver*, and *strategic* (16). The control task concerns the actual vehicle handling, i.e., longitudinal and lateral control of the car. Time constraints at control level are usually below 1 s, and reaction time is critical for performance at the control level. It is also a task which requires more or less continuous attention. The maneuvering level includes interactions with other road users such as overtaking maneuvers. For these tasks time constants are normally between 1 to 10 s. Trip planning and navigation represent tasks at a strategic level. Such tasks are usually not time critical and the time frame is usually about 10 s or above. For drivers with SCI we are primarily concerned with the control and maneuver levels, where one could expect to find differences between SCI drivers and non-disabled drivers. To safely investigate such differences, a driving simulator is suitable. Reaction time to unexpected critical events could be used to assess differences in risk level. Although drivers with SCI use hand controls, which might improve reaction time (17), their impairment might, on the other hand, increase reaction time (18).

Workload is another critical aspect of the driving task for drivers with SCI. Driving a car is normally not particularly physically loading for non-disabled drivers. But, for a driver with tetraplegia, who has to do with two impaired limbs what a non-disabled individual can use four limbs to do, driving is occasionally experienced as tiresome, even if the car is adapted. As a consequence, many drivers with disabilities avoid driving longer distances (19). Physical workload and endurance are thus critical factors for drivers with SCI. Furthermore, driver fatigue, which could be a consequence of extended workload, is considered an important factor behind many road accidents (20). There are basically four different methods to measure workload: subjective rating methods, physiological methods, and primary and secondary task performance (21). Subjective rating scales are easy and simple to use, and they are also reliable tools.

The following experiment was carried out based on the discussion above in order to establish a baseline for the development of an adaptation evaluation method. The potential differences between SCI and non-disabled drivers revealed in this experiment could thus be partly explained by insufficient adaptation.

The purpose of the experiment was to examine driver performance and limitations of drivers with tetraplegia and to investigate how different adaptation designs influenced the driver's performance and imposed workload. For this purpose drivers with tetraplegia were compared to a matched group of able-bodied drivers. The experimental group was divided into two groups, equal in size, depending on what hand control system they used, separate or combined levers for accelerator and brake control. The two groups were identified as single- and dual-lever drivers. The purpose was *not* to assess a certain group of drivers with disabilities in order to determine whether they should be restricted or not permitted to drive.

METHODS

Subjects

Fifty-two subjects, 26 with tetraplegia and 26 able-bodied, participated in the study. The subjects in the experimental group were all paralyzed from the level of their nipples down to their toes due to a lesion in the cervical region of the spine. The position of lesions varied between subjects from the 5th (C5) to the 7th (C7) cervical vertebra (**Table 1**). The character of the lesions varied, between subjects, from complete to incomplete. An experienced driving instructor considered the subjects' functional impairment to be approximately equal with respect to the kind of adaptation needed for controlling the car. Only 2 of the 26 subjects were female, less than 10 percent, which was somewhat low compared to the overall SCI population (18 percent). The drivers with SCI were between 22 and 60 years old, with a median age of 36 years, and had driving experience using adapted cars, which varied from 4 to 40 years, with a median of 17 years. Their annual driving distance varied between 10,000 and 45,000 km with a median distance of 15,500 km. The subjects were assigned to drive with the same type of hand control they used in their own car.

The control group was selected to individually match the experimental group according to gender (24 males and 2 females), age (24 to 56 years, median 37 years), driving experience (driving license 5 to 36 years, median 17 years), and distance driven per year (10,000 to 45,000 km, median 15,500 km).

Table 1.
Distribution of injury in drivers with SCI

Level	Single-lever drivers	Dual-level drivers	Total
C5-C6	8	6	14
C6-C7	3	5	8
C6	1	0	1
C7	1	2	3

Apparatus

A dynamic, high-fidelity driving simulator was used (23,24). The simulator consisted of a moving base system, a wide-angle image system, a vibration-generating system, a sound system, and a temperature-regulating system (**Table 2**). These systems were controlled to give the impression of actually driving a car.

Table 2.
Technical data for the VTI driving simulator

Simulator subsystem	Data
Vibrations	
vertical	5 cm
longitudinal	7.5 cm
roll	7°
Motion	
pitch	24°
roll	24°
lateral	3 m
max. acceleration	0.4 g
Visual system	
forward field of view	120° × 30°
resolution	3100 × 625 pixels
time delay	20 ms

A number of validation studies have been performed successfully in this simulator (25). These studies showed that the moving base system was important for the experienced reality and external validity (**Figure 1**).

The car body used in the simulator was a front part of a Saab 9000 with an automatic gearbox. Noise, infrasound, and vibration levels inside the car corresponded to what is found in modern passenger cars. As the entrance to the car was 2 m above ground level, a wheelchair lift was installed to make it accessible. A ramp outside the car body was positioned so that the wheelchair and the driver's seat were at the same level in order to facilitate the transfer. Some SCI subjects used a sliding plate to transfer to the driver's seat. If a subject requested it, an experimental leader would give help to transfer.

Two commonly used hand controls for accelerating and braking were installed in the simulator. This facilitated the recruitment of SCI subjects. The hand controls were principally different in design, as one had two separate levers and the other had one combined lever for

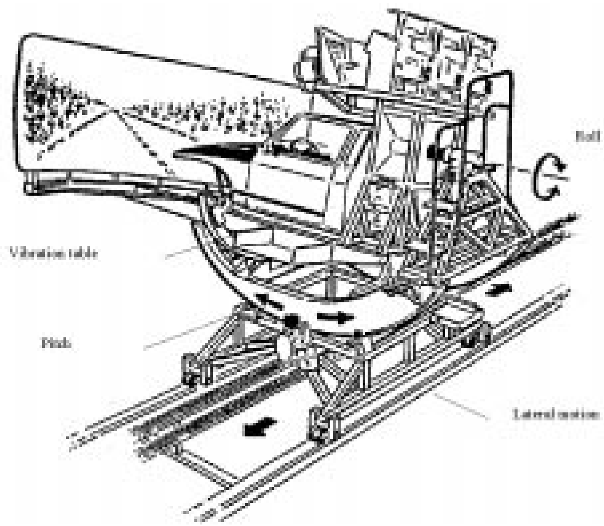

Figure 1.
The moving base and vibration system of the driving simulator.

accelerating and braking (**Figure 2**). The positions of the two hand controls were also different. The combined lever system was operated by pushing the lever to brake and pulling to accelerate. The system with separate levers was mounted on the steering column. The braking lever was operated by pushing it forward, while the driver accelerated by moving the other lever radially downwards. Both systems had their pros and cons. With the single lever system the driver did not have to switch from one lever to the other in order to control accelerator and brake. On the other hand, the motion of the lever required to change from speed control to braking could prolong reaction time. Also, the position of the lever made it impossible for the driver to use more than one hand for steering. The dual lever system let the driver have two hands on the steering wheel, but on the other hand speed control could interfere with steering control. Furthermore, the driver had to transfer from accelerator lever to brake lever in a critical situation, which could prolong reaction time. Which system the driver will select in his/her own car depends very much on previous experience or recommendations from providers, friends, or individual traffic inspectors. None of the systems is specifically considered to be superior to the other by responsible authorities. In addition to the hand controls, one of two types of steering knobs was mounted on the steering wheel if the subject had such an adaptation in his/her own car.

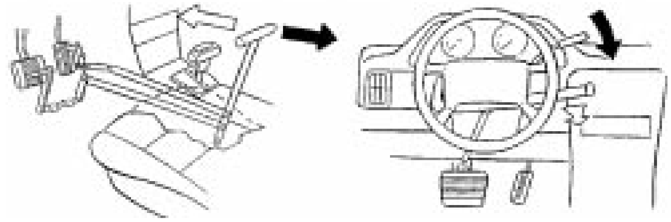

Figure 2.
The two hand controls used in the experiment. To the right, the single lever system and to the left, the system with separate levers accelerating and braking. The empty arrows indicate the direction for braking, and the filled arrows for accelerating (from reference 35, with permission).

The power-assisted brakes were adapted if a SCI subject was not able to exert the force needed to lock the brakes (380 N) on the brake lever. “Comfortable” braking level was recorded and if the recorded force was greater than 75 percent of the subject’s maximum force (<380 N), then the brakes were adapted so the exerting maximum force corresponded to 380 N. If “comfortable” braking instead resulted in a force less than 75 percent of the subject’s maximum force (<380 N), then the brakes were adapted so the “comfortable” level corresponded to 75 percent of maximum force, and the maximum force was scaled to correspond to 380 N. The power-assisted steering could be augmented so that only half the force was required to steer. This was done if required and if the driver was used to such an adaptation from his/her own car. This procedure was derived from praxis used by experienced car adaptation companies.

The Driving Task

All subjects drove the same route and were exposed to the same situations and events. The route was 80 km long and consisted of two consecutive sections, each 40 km, with the same geometry. The road was a 2-lane, nine-meter-wide asphalt road with high friction. The weather was slightly cloudy with an average sight distance of 400 m.

Ninety-six, 48 in each half, oncoming cars appeared randomly along the route. The purpose was to increase workload and realism. Twenty-four cars were parked on the right side along the route, 12 along each half. In 4 of these situations, oncoming cars were encountered 40 m before passing the parked cars. A specific situation was created to force the subjects to make an evasive maneuver. On four occasions parked cars on the right side of the road started to drive and turn left as the driver approached.

Visual stimuli, presented at the left side of the road, were used to simulate unexpected traffic events. The stimuli were 4 × 4 cm red or yellow squares presented 2.5 m from the driver's eyes, representing an approximate sight angle of 1°. The subjects were instructed to brake as fast as possible for red squares and to ignore yellow squares. These situations occurred eight times in random order, four red and four yellow squares, for each subject.

Measures

A number of dependent variables were used to analyze driving performance and workload. Data were calculated and recorded, with a frequency of 2 Hz. Questionnaires were used to capture subjective data and background information. Means were calculated for individual subjects, and standard deviation (S.D.) was used as a measure of variation.

Speed, speed variation, lateral position, variation of lateral position, distance to overtaken cars, and reaction time were used as performance measures. Lateral position was calculated as the distance from the center line of the road to lateral position of center of the steering wheel. Standard deviation of lateral position was used as a measure of the driver's steering control. Brake reaction time in seconds was calculated as the time elapsed from display of visual stimulus until the brake (foot or hand-controlled) was depressed with a force greater or equal to 0.05 N. The resolution was 20 ms. If there was no response within 5 s, the stimulus was removed. Mean reaction time was calculated for each subject.

Workload was measured with a subjective rating scale. The Task Load Index, NASA-TLX (26) that proved to be superior to other rating scales in a study by Hill (22) was used in a simplified form (Raw Task Load Index) NASA-RTLX (27) to assess the subjects' overall workload. The NASA-TLX has been used and validated for a broad variety of activities and is frequently used in traffic safety research. The subjects estimated six workload factors: *mental demand*, *physical demand*, *time pressure*, *performance*, *effort*, and *frustration levels* on a continuous scale ranging from very low to very high (0–100) after completion of the driving task. The subjects rated their workload based on six different questions, such as *"How much physical activity was required (e.g. pushing, pulling, turning, controlling, activating, et cetera)?" "Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?"* (Physical demand), and *"How hard did you have to work (mentally and physically) to accomplish your level of performance?"* (Effort).

Static force capacity was measured immediately before and after driving. The SCI subjects exerted a static force on the brake lever and kept it for 20 s, then released the pressure and rested for 5 s. This was repeated five times before and after driving. The initial phase, 5 s, of the force measuring was excluded and only the steady state or declining phase, 5–20 s, was used to calculate a mean force capacity for each subject.

Questions concerning gender, age, driver's license, annual distance driven, driving experience, and driving habits were answered by all subjects. The SCI subjects also answered questions concerning their injury and what kind of adaptations they had in their own cars. Experienced realism and specific questions about steering, braking, and accelerating control were asked in a separate questionnaire.

RESULTS

Driving Performance

Group means were calculated and one-way ANOVAs were used to evaluate the results and a significance level was set to $p<0.05$. The average speed over the total distance for drivers with tetraplegia was 91.3 km/h, while it was 88.4 km/h for the control group. Mean speed for the two SCI subgroups was 93.4 km/h and 89.2 km/h for single- and dual-lever users, respectively. However, none of these differences was significant. Furthermore, analyses of variation in speed revealed no significant differences between the groups, neither for the total test route nor for the two 40-km halves separately. As the two sections of the route were equal, data on speed variation per section was also analyzed. It turned out that variation in speed was higher for all groups during the second part of the route (**Table 3**). The differences, however, were nonsignificant.

Table 3.
Mean and variation (standard deviation) in speed (km/h) for first and second half of the experimental route

Group	First 40 km (means/S.D.)	Second 40 km (mean/S.D.)
Tetraplegics		
single lever	92.8/8.74	94.0/10.75
dual lever	89.2/9.64	89.2/11.90
Total	91.0/9.19	91.6/11.32
Able-bodied		
"single-lever controls"	88.9/9.35	89.1/11.19
"dual-lever controls"	86.8/10.64	89.0/12.65
Total	87.9/10.00	89.0/11.92

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The results of the choice reaction-braking task, with red and yellow square stimuli, are shown in **Table 4**. Mean reaction time for the tetraplegic individuals was 0.90 s and for the control group 0.80 s. The difference between drivers with tetraplegia and control drivers, 0.10 s, was significant [$F(1,50)=6.53$, $p=0.014$]. The difference between the two groups of drivers with tetraplegia and their respective control groups was only significant for the dual-lever group [$F(1,24)=4.35$, $p=0.048$]. However, the difference between single- and dual-lever groups was not significant.

Table 4.
Average brake reaction times for experimental and control groups

Group	Mean reaction times
Tetraplegics	
single lever	0.88
duel lever	0.93
Total	0.90
Able-bodied	
“single-lever controls”	0.81
“dual-lever controls”	0.79
Total	0.80

The mean lateral position for all straight sections of the route was calculated for each subject. Only straight sections were used for this analysis, as curve taking can be very individual, a difference of no relevance in this case. The differences were not significant, neither between tetraplegics and controls, nor between the two subgroups of tetraplegics.

The mean variation in lateral lane position was calculated over all straight sections of the route for each subject. There was no significant difference between the drivers with tetraplegia, S.D.=0.43 m, and the control group S.D.=0.47 m. However, the tetraplegics driving with dual-lever controls had a variation in lateral lane position that was S.D.=0.47 m. This was significantly greater than for those using the single lever control, S.D.=0.40 m, [$F(1,24)=5.30$, $p=0.030$]. Steering performance was also analyzed while the subjects braked in response to the red squares, but no significant differences were found.

The evasive maneuvers were analyzed with the following derived measures: minimum passing distance to parked car, speed when passing the parked car, and maximum left position during overtaking. There were no significant differences, neither between experimental and control group, nor between the two experimental subgroups.

Workload, Endurance and Questionnaires

Group means of the six workload factors—mental demand, physical demand, time pressure, performance, effort, and frustration—of NASA-RTLX were calculated and analyzed (**Figure 3**). The subjects with tetraplegia estimated their effort as greater and experienced a greater time pressure compared to the control group. These differences were significant for time pressure [$F(1,50)=8.42$, $p=0.006$] and effort [$F(1,50)=4.01$, $p=0.050$]. Other differences between the groups were not significant. The two subgroups with SCI did not differ significantly in their ratings.

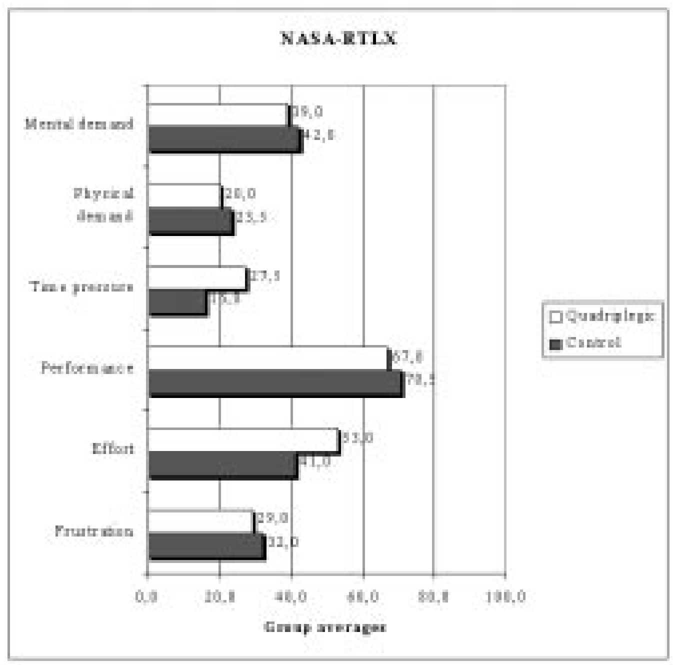

Figure 3.
Group averages for ratings on the six NASA-RTLX scales for tetraplegic and control drivers.

Static force measurements were taken for drivers with SCI before and after the driving task using the brake levers (**Figure 2**). The average force before was 448 N for the single-lever users and 349 N for the dual-lever users. This difference was significant [$F(1,24)=7,59$, $p=0.011$]. Corresponding forces after driving were 428 N and 315 N, respectively, which also was significantly different [$F(1,24)=12.88$, $p=0.001$].

The difference between initial and final force levels for the two groups were, however, not significant. The ratio between before and after mean forces was 0.97 (single) and 0.92 (dual). Also, this difference was nonsignificant.

The subjects answered a specific question, “Do you think it was tiring to brake and accelerate?” with a rating on a scale ranging from 1 for “very tiring” to 7 for “not at all tiring.” The average for the tetraplegic group was 5.69 and the corresponding value for the control group was 6.84. This difference was significant [$F(1,50)=12.20$, $p=0.001$]. The subjects driving with the single-lever control thought it was physically more tiring to brake and accelerate, mean 5.08, compared to the dual-lever group, mean 6.31. This difference was significant [$F(1,24)=4.10$, $p=0.050$]

Steering and speed performance data were also considered to be a possible way to reveal signs of fatigue. Increased variation in lateral and longitudinal control would then indicate possible signs of fatigue due to physical workload. The analysis of speed control showed that speed variation was higher for the second part of the test route, but the differences were not significant.

The subjects were asked questions concerning how well they thought they could steer, brake, and accelerate in the simulator. They gave their answers on a 7-point scale ranging from “not at all well” to “very well.” They were also asked about the realism in the simulator and gave their answers on the same type of scale, ranging from “not at all realistic” to “very realistic.” The results are given in **Table 5**. The only significant difference was that the single-lever drivers thought that they could control the brake better, compared to the other group of drivers with tetraplegia [$F(1,24)=5.27$, $p=0.031$].

Table 5.
Group means for answers on questions concerning steering, braking, accelerating, and simulator realism

Group	Steer	Brake	Accelerate	Realism
Tetraplegics				
single lever	6.2	6.8	6.2	4.9
dual lever	6.5	5.6	5.5	5.4
Total	6.3	6.2	5.8	5.2
Able-bodied				
“single-lever controls”	6.4	6.2	5.8	4.8
“dual-lever controls”	6.2	5.4	6.1	5.1
Total	6.3	5.8	5.9	5.0

DISCUSSION

Driving performance of drivers with tetraplegia was evaluated from safety and workload point of view. In such an evaluation it is important that the results are related to driving as experienced on the road and that relevant measures are used (15). The driving task, in this experiment, included speed control, road following, interacting with other road users, and reacting to unexpected events. Performance, reaction time, workload, and endurance were used to assess driver behavior and condition. For high controllability and safety reasons the experiment was performed in a dynamic driving simulator. The motion system of the simulator has shown to contribute to the experience of reality (25). This was considered important with respect to drivers with tetraplegia, as they are, due to their impairment, sensitive to forces, which might influence their trunk stability.

Driving Performance

Since there are no norms that can be used to determine whether specific driving behavior is safe or not, a matched group of able-bodied drivers using conventional car controls was used as reference. From a traffic safety point of view, drivers with tetraplegia are required to perform the driving task equally as well as able-bodied drivers in standard cars (28). Regulations specify that the car should be adapted so that the driver’s impairment is fully compensated. Even if the car is adapted it is likely that drivers with tetraplegia will be closer to the limit of their resources. This hypothesis is supported by the finding that drivers with disabilities avoid long-distance driving (19). Inappropriate or inadequate adaptation could lead to severe consequences beyond limited mobility. Too many adaptations do not fulfil the adaptation requirements as specified by Koppa (7). All of these requirements were not possible to test in this setting, but focus was on control and maneuver performance in a rural road environment.

The analysis of the general driving performance measures such as speed and lateral lane position did not reveal any significant differences between the tetraplegic and control groups. The type of hand control used had no influence either. Thus the gross overall driving behavior was similar for the two groups. This supports the proposition that the adaptation was adequate.

The average speed level did not differ significantly between the groups, which indicates that they all drove quite similarly with respect to speed choice. The standard deviation in speed was greater for the second half of the 80-km long test route for all drivers. Even though this difference was not significant, it seems to indicate that subjects deteriorated in their speed control, and this could be a sign of fatigue. It was also noted that for the group driving with the dual lever system, this difference (**Table 3**) was almost significant ($p=0.054$).

Considering the reaction time results, drivers with tetraplegia were about 10 percent slower than able-bodied drivers. It could be debated whether this result was an indication of inadequate adaptation with possible safety consequences or if it should be considered as an acceptable deviation. Reaction times for both groups seemed to be fully acceptable compared to other findings. Green (29) analyzed reaction-time results derived from simulator studies, controlled road studies, and naturalistic observation and concluded that brake reaction times vary between 0.7 and 1.5 s, depending on the driver's expectation. Subjects in this study were instructed to brake as fast as possible and were fairly prepared for the events. Nilsson and Alm (30) found in a simulator study that young drivers had a mean reaction time of 0.95 s compared to a mean of 1.34 s for a group of elderly (+65) drivers. Johansson and Rumar (31) reported from an on-the-road study with more than 300 drivers that the median brake reaction time was 0.9 s. Thus, it can be argued that the adaptation of hand controls compensated for the drivers' disabilities.

It was expected that the reaction times for the group driving with the single lever would be shorter compared to those driving with the separate brake lever. For instance, Richter and Hyman (17) found that reaction time improved by 25 perfent with a hand-operated brake control because drivers did not have to move from the accelerator to the brake. Even if there was a difference (**Table 4**) in that direction it was not significant. However, the difference between the tetraplegic and the control groups seems to be most pronounced for those driving with the dual lever system. The difference between this group and its control group was significant. This seems to suggest that there was an influence on reaction time, which could be attributed to the design of the controls.

There were no differences in average lateral lane position for straight sections between the groups, which suggests that all four groups positioned the car in the lane in a similar fashion. The variation (S.D.) in lateral lane position showed, though, an interesting result. It was expected that driving with the single lever would have some negative impact on the steering control, as the lever's location implies "one hand steering." Instead the tetraplegics using the dual-lever control had 0.07-m greater S.D. in lateral lane position. One explanation for this result can be an interference between speed control and steering control. The dual-lever speed control, placed on the steering column, is operated radially and permits the driver to keep the right hand simultaneously on both the steering wheel and the speed control. However, there was no difference, in total, between the drivers with tetraplegia and the able-bodied drivers. This result supports also the suggestion that adaptation design differences can influence driving performance. In order to further develop the lateral control performance as a measure to investigate adaptation design it would be valuable to explore the use of the time-to-line-crossing (TLC) concept (32,33). The TLC is a time-dependent measure, which can be used to investigate steering control performance.

The analysis of the evasive maneuvers did not reveal any significant differences between any of the groups. The idea was to investigate a task, which required increased simultaneous lateral and longitudinal control of the car in order to find out how well the different adaptations supported the drivers in such a situation. There are at least three possible explanations for this result. One is that the maneuvers were too easy to reveal any differences. Another possibility is that the situation included an oncoming car that was controlled in such a way that the meeting point was the same for all subjects. This forced the drivers into similar maneuver patterns. Finally, both hand-control systems could be seen as adequate. A more demanding maneuver, for example, a double lane change, could possibly be used for further investigations. Such a task was used in a closed-track experiment with severely disabled drivers who drove their own four-way joystick-controlled car and revealed some difficulties that were considered to be caused by the adaptation (34).

Workload, Endurance and Questionnaires

The workload assessment included both mental and physical aspects of the driving task. Of the six workload factors of NASA-RTLX, three—mental demand, physical demand, and Frustration—were, surprisingly, greater for the able-bodied drivers compared to the tetraplegics. These differences, however, were not significant. The only significant difference was that drivers with tetraplegia experienced a greater time pressure and exerted more effort. This seems to indicate that the tetraplegics found the driving task more loading than did the able-bodied drivers. This suggestion was supported by the result of the explicit question, “Do you think it was tiring to brake and accelerate?” The result was also in accordance with what was found in interviews with drivers with disabilities (19). The analysis of the NASA-RTLX did not reveal any differences between the two groups of tetraplegics. However, drivers using the single-lever control indicated, in their answers to the question mentioned above, a higher degree of tiredness. This was probably due to the position of the control lever, between the front seats, where there was no support for the arm, which led to an uncomfortable arm posture. The results from the static force measures did not, however, show any significant decrease in force capacity. Thus, the experienced tiredness cannot be explained by local fatigue in the driver’s arm. Changes in speed variation (S.D.) as an indicator of increased workload for the single-lever drivers did not support the finding of greater tiredness for the group. It was found that speed variation increased more for the dual-lever users, but this was probably due to interference between speed and steering control for that adaptation.

The experienced realism in the simulator is important with reference to the validity of the findings in real driving conditions. The simulator used in this study is one of the few driving simulators in which validation studies have been successfully performed (25). The analysis of the responses to the questions of steering, braking and accelerating realism did not show any significant differences between the groups. But the results, 5.5—6.8 on a 7-graded scale, indicated that the drivers experienced simulator driving as quite naturalistic (**Table 5**). This was also supported by answer to the question regarding experienced realism in the simulator. The result was good considering the limited possibilities for adapting the simulator. Differences between the simulator and the subjects’ own individually adapted cars might also have contributed to differences between the groups. This is not, however, a major problem, as the objective was not to assess drivers, but adaptations. Furthermore, it can be noted that the scores for steering are somewhat higher compared to braking and accelerating (**Table 5**). This is consistent with experiences from other experiments in the simulator and can possibly be explained by the differences in the lateral and longitudinal motion system (**Figure 1**).

CONCLUSIONS

There were no great differences in general driving behavior between the groups. However, drivers with tetraplegia had a somewhat longer reaction time compared to the control group. They also experienced the driving task as more loading and spent more effort in order to perform at the level they did. The observed differences could be an indication of insufficient adaptation. Differences in driving performance and workload between the two subgroups of drivers with tetraplegia could be interpreted as indications of design imperfections in the hand-control systems used in this study. However, the method applied in this experiment needs to be further developed and refined before it can be used to evaluate different adaptations solutions.

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